

Compact Ocean Models Enable Onboard AUV Autonomy and Decentralized Adaptive Sampling

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LONG-TERM GOALS

Improve synoptic observations and enhance ocean prediction through development of new capabilities for persistent underwater ocean surveillance.

OBJECTIVES

Multi-platform ocean observing systems are typically centrally controlled from shore, limiting their ability to adapt to new observations which would inform more effective sampling strategies. Our objectives are:

1. Enhance the ability of mobile agents to respond adaptively by providing them with a synoptic realization of the environment in the form of compact models of the observed ocean, similar to [Frolov et al., 2009; van der Merwe et al., 2007a].
2. Develop compact representation of the ocean models that can be economically computed or transmitted onboard an AUV.

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3. Develop algorithms for adaptive planning of AUV surveys.
4. Validate the developed compact ocean models and onboard planning algorithms in a vehicle simulation environment for Monterey Bay.
5. Demonstrate use of compact ocean models onboard a long-range AUV during a field deployment.

APPROACH

To enhance the ability of mobile agents to respond to dynamic events in the ocean, we used the following approach:

1. To enhance the on-board decision making capabilities, we developed compact ocean models that can bring synoptic information on-board a mobile platform.
2. To benefit from additional information provided by synoptic models, we developed a combination of path-planning and data assimilation techniques that can be used either on-shore or on-board the vehicle.
3. To test the newly developed technology in practice, we developed a set of use-cases.

WORK COMPLETED

1. Compact models of synoptic circulation:
 - a. Developed a statistical model for surface currents in Monterey Bay [Frolov et.al., 2012a].
 - b. Studied feasibility of porting HF-Radar prediction capabilities to a new location, off the coast of South Carolina (summer intern, 2012) and off the Basque region in Spain (collaboration with Jeff Paduan at NPS).
 - c. Ported model emulator code on-board the long-range AUV.
 - d. Completed two deployments running the on-board emulator code in the field with periodic updates based on HF radar observations, sent automatically from shore, via satellite communications. Moving toward integration with navigation code to enhance dead reckoning.
2. Data assimilation system:
 - a. Published results on data assimilation system for assimilating bio-optical data into a coupled physical-biogeochemical model of Monterey Bay [Shulman et.al. 2013].
 - b. Developed and tested (using twin data) a data assimilation system for on-board assimilation of AUV-measured surface currents into an on-board model of surface currents [Frolov et.al. 2012b].
3. Use cases:
 - a. Synoptic sampling of algal blooms off the U.S. West Coast [Frolov et.al. 2012c, Frolov et.al. 2011a].
 - b. Tracking of biological processes in Lagrangian Coherent Structures using AUVs [Frolov et. al 2011b].

- c. Persistent monitoring of algal blooms using a Wave Glider platform [Frolov et. al 2011c].

RESULTS

COMPACT OCEAN MODELS

Originally, we proposed to develop compact models based on 3D circulation models for Monterey Bay. However, our evaluation of existing circulation models showed that their accuracy and resolution was insufficient for planning of advanced sampling strategies. Instead, we decided to develop compact models based on surface current data available from HF-radar system in Monterey Bay.

We developed a linear statistical model for predicting surface currents (up to 48 hours in the future) based on a short time-history of past HF-radar observations (past 48 hours) and an optional forecast of surface winds. Our model used empirical orthogonal functions (EOFs) to capture spatial correlations in the HF-radar data and used a linear autoregression model to predict the temporal dynamics of the EOF coefficients. We tested the developed statistical model using historical observations of surface currents in Monterey Bay, California. The predicted particle trajectories separated from particles advected with HF-radar data at a rate of 4.4 km/day. The developed model was more accurate than an existing statistical model (drifter separation of 5.5 km/day) and a circulation model (drifter separation of 8.9 km/day), as illustrated in Figure 1. We found that the minimal length of the HF-radar data required to train an accurate statistical model was between one and two years, depending on the accuracy desired. Our evaluation showed that the developed model is accurate, is easier to implement and maintain than existing statistical and circulation models, and can be relocated to other coastal systems of similar complexity that have a sufficient history of HF-radar observations.

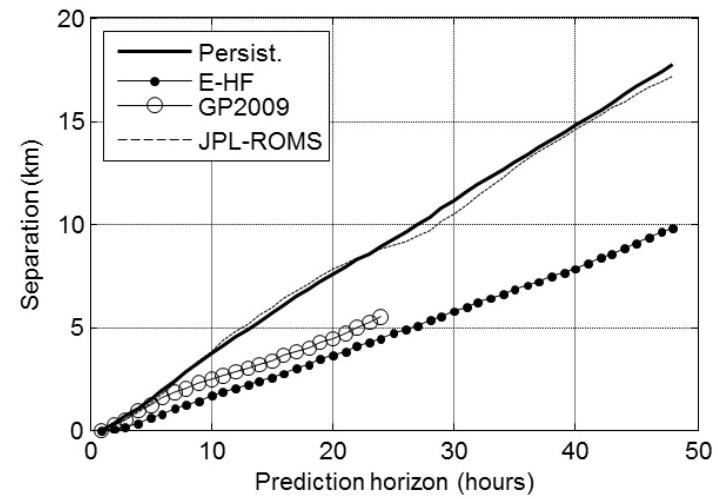


Figure 1: Prediction errors -- represented by drifter separation -- from 3 different models: Emulators developed in this project, statistical models described in GP2009 [Garfield et.al. 2009], and a ROMS circulation model. The emulators developed in this project have the lowest drifter separation of the methods compared here.

We conducted two field trials with the onboard emulator running on a Tethys-class long-range AUV and estimating the surface current at the location of the LRAUV. These trials included automating shore-side tools to pull the most recent HF radar observations, project the data into the EOF subspace that the emulator runs in, and send the projected data to the vehicle periodically via Iridium satellite communication. These trials have proven useful in testing and debugging the onboard implementation of the compact ocean models code, and provided useful data for the push toward integrating estimated surface currents into the vehicle navigation code.

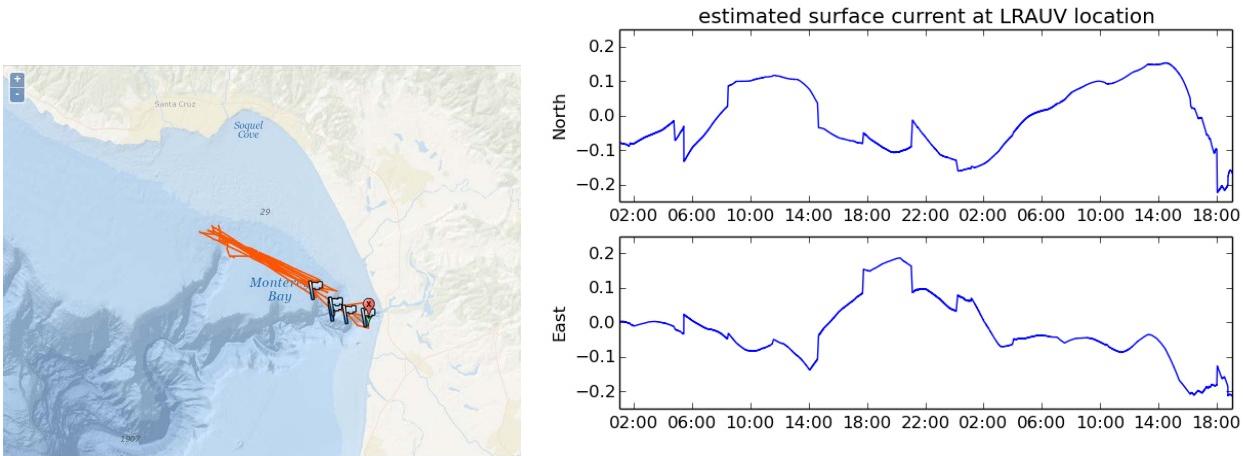
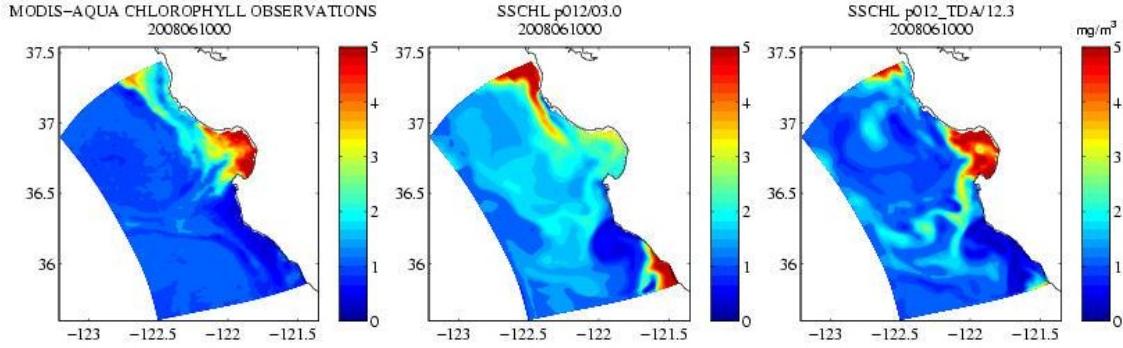


Figure 2: Field trial using onboard emulator to estimate surface current at LRAUV location. Left panel shows vehicle track and right panel shows estimated surface currents over time.

DATA ASSIMILATION

Impact of bio-optical data assimilation on short-term coupled physical, bio-optical model predictions

To test future observing strategies, we developed a system for assimilation of bio-optical measurements into a fully-coupled ecosystem model of Monterey Bay. The Monterey Bay model consists of a physical model based on the Navy Coastal Ocean Model (NCOM) and a biochemical model which includes three nutrients, two phytoplankton groups (diatoms and small phytoplankton), two groups of zooplankton grazers, and two detrital pools. The Navy Coupled Ocean Data Assimilation (NCODA) system was used to assimilate physical observations. For the assimilation of bio-optical observations, we used a stationary Kalman filter with the error covariances specified in the subspace of the multivariate (bio-optical, physical) empirical orthogonal functions (EOFs) estimated from a month-long model run. With the assimilation of satellite-derived bio-optical properties (chlorophyll-a and absorption due to phytoplankton), the model was able to reproduce intensity and tendencies in surface and subsurface chlorophyll distributions observed at water samples locations in the Monterey Bay, CA (Figure 3).



2a) MODIS Chl-a

2b) without data assimilation

Figure 3: Improvements in simulated surface Chl-a. In the vicinity of Monterey Bay, the simulated results using data assimilation match the observation from MODIS much more closely than the simulated results without data assimilation.

Impact of on-board assimilation of surface currents into a statistical model of surface currents

To enable greater autonomy for underwater vehicles, we developed a compact ocean modeling and assimilation system that can be deployed on-board of an underwater vehicle. The developed system estimates a synoptic picture of surface ocean currents by assimilating data from the vehicle underway system. As a result, we can bypass communication bandwidth and delay limitations by assembling both synoptic and local data on a vehicle.

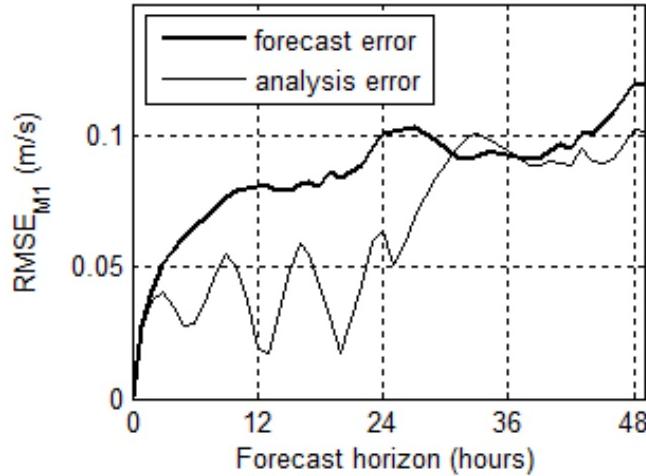


Figure 4: Assimilation errors at mooring M1 as a function of the forecast horizon. RMSE were averaged over 305 two-day assimilation cycles that were run between 2010/01/01 and 2010/11/01.

The developed modeling system is based on a statistical model that is trained to emulate the dynamics of surface currents observed by HF-Radar (see section on compact ocean models, above). Our data assimilation system is implemented using a reduced-dimension Kalman filter that operates in the EOF space (similar to Frolov et.al. 2008). We test the performance of the system in a series of computational experiments, where we assimilate underway velocity measurements along simulated tracks. Our experiments showed improvements in predicted currents up to 25 km away from the vehicle. Within the first 10 km, assimilation of data was able to improve the nowcast results, as well as the forecasts up to 6 hours in the future. Average errors in the nowcast model were reduced by a factor of two, from 0.07 m/s to 0.036 m/s (Figure 4).

USE CASES

Tracking of biological processes in Lagrangian Coherent Structures using AUVs

One potential application for the enhanced surface current prediction and assimilation method developed in earlier sections is adaptive tracking of biological features in front-like structures associated with Lagrangian coherent structures (LCS). To understand the feasibility of such field program, we reviewed past observational data from AUV missions in Monterey Bay (~50 transacts over five years). We found a strong change in biological properties coincided with an LCS in 50% of the cases. For example, a strong change in Chl-a fluorescence associated with an attracting LCS is shown in Figure 5.

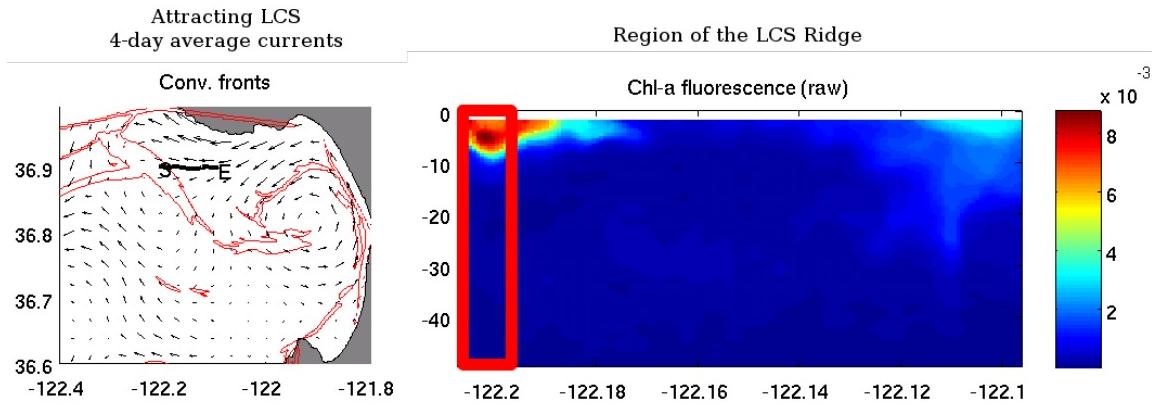


Figure 5: Biological processes associated with Lagrangian coherent structures. (a) Attracting LCS valid for 06/21/2011 overlaid on top of 4-day average of surface currents. (b) AUV-observed transect of Chl-a. LCS ridge is highlighted in a red box.

Persistent monitoring of algal blooms using a Wave Glider autonomous surface vehicle

We tested the path planning methods developed in previous years using wave glider (WG)—a novel autonomous surface vehicle that uses energy from surface waves for propulsion and an array of solar panels to power the sensor and hotel payloads. Our goal was to use WG for persistent monitoring of algal biomass distribution in Monterey Bay, CA. In October of 2010, we operated the WG along three pre-determined synoptic sampling paths in northern and central Monterey Bay (chosen in part based on the optimal path-planning strategy developed under this funding). The WG successfully collected 17 days of data, traveling at an average speed of 0.5 m/s for a total of 600 km. The WG operated in variable sea states (significant swell height from 0.8 m to 3.3 m) and ambient current conditions (from 0 to 1 m/s). The real-time data collected by the WG were used to target secondary sampling of high-biomass areas with high-value assets, such as ships and autonomous underwater vehicles. The results of our field experiment showed that WG is a capable platform for persistent, low-cost monitoring of algal biomass distribution. The performance of the WG was robust under diverse surface current and wave conditions. The experience with the WG in other applications suggests that the platform can be deployed for the entire duration of the bloom season, with the service periods determined by the bio-fouling of sensors and not by the platform endurance. Comparing underway data from WG and other in-situ platforms showed lower in-situ Chl-a concentrations than the satellite data, suggesting positive bias in satellite imagery (Figure 6).

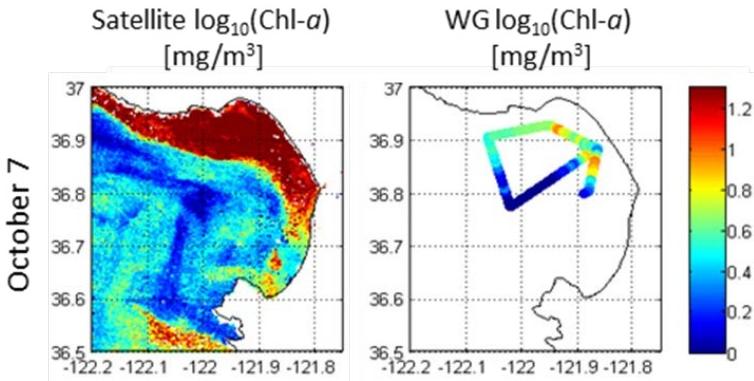


Figure 6: Comparison of Chl-a estimates from satellite imagery (left column) and WG (right column). Satellite imagery is from the Envisat satellite MERIS sensor. WG track is shown for one day before and after the satellite image on the left was acquired.

IMPACT/APPLICATIONS

- This project has developed the first implementation of a circulation model that can be run on small AUVs in real time, providing a foundation for model-driven adaptive sampling in situ.
- Developed compact models for prediction of surface currents. These are under consideration to be used operationally as a part of IOOS surface current datasets. A draft implementation is being used in the Fall 2013 MBARI CANON field experiment.
- Developed data assimilation tools for bio-optical data assimilation that are currently in use by researchers from the U.S. Naval Research Laboratory.
- Analysis of AUV and LCS data forms a foundation for future field programs at MBARI that will focus on better understanding of ecosystem processes in front-like features.
- Published analysis of sampling strategies for algal blooms that are likely to affect future designs for operations and research on harmful algal blooms.

TRANSITIONS

The current prediction code developed in this project has been provided to the Naval Postgraduate School to be used as the basis of a new prediction product for their HF radar facility.

RELATED PROJECTS

NRL internal project BIOSPACE: development of data assimilation capabilities was in part supported by the NRL internal BIOSPACE project. BIOSPACE aims at developing tools that can enable prediction of optical properties of the coastal ocean on 3-5 day timescales. In October 2010, the BIOSPACE field program was focused on evolution of optical properties of the water in northern Monterey Bay.

MBARI internal project CANON: Field testing of the optimal survey design methods is supported with MBARI internal project CANON. CANON aims at developing new Lagrangian observing systems that can study the dynamics of marine ecosystems by following their evolution in time and space. In

October 2010, the CANON field program was focused on following emergence, growth, and decay of phytoplankton bloom patches in Monterey Bay.

REFERENCES

- Frolov, S., A. M. Baptista, Y. Zhang, C. Seaton, (2009). “Estimation of Ecologically Significant Circulation Features of the Columbia River Estuary and Plume Using a Reduced-Dimension Kalman Filter”, *Continental Shelf Research*.
- van der Merwe, R., Leen, T. K., Lu, Z., Frolov, S., and Baptista, A. M. (2007), “Fast Neural Network Surrogates for Very High Dimensional Physics-Based Models in Computational Oceanography,” *Neural Networks*, 20, 462-478.
- Garfield, N., Paduan, J. D., & Ohlmann, C. (2009). “Delivery and Quality Assurance of Short-Term Trajectory Forecasts from HF Radar Observations” (p. 28). Durham, New Hampshire: Final Report, Project Number: 07-061. The Coastal Response Research Center.

PUBLICATIONS

- Shulman I., Frolov, S., Stephanie Cayula, Brad Penta, Rick Gould, Peter Sakalauskus, Sherwin Ladner (2013) “Impact of bio-optical data assimilation on short-term coupled physical, bio-optical model predictions”, *Journal of Geophysical Research*. ([DOI: 10.1002/jgrc.20177](https://doi.org/10.1002/jgrc.20177)) [published, refereed]
- Frolov, S., J. Paduan, M. Cook, J. Bellingham (2012a) “Improved statistical prediction of surface currents based on historic HF-Radar observations”, *Ocean Dynamics*.
([DOI: 10.1007/s10236-012-0553-5](https://doi.org/10.1007/s10236-012-0553-5)) [published, refereed]
- Frolov, S., J., Bellingham (2012b) “Compact ocean models enhance onboard autonomy of underwater vehicles”, in *Proc. AGU Ocean Science Meeting*, Salt Lake City, UT. [published]
- Frolov, S., R., Kudela, J., Bellingham (2012c) “Monitoring of harmful algal blooms in the era of diminishing resources: a case study of the U.S. West Coast”, *Harmful Algae*.
([DOI: 10.1016/j.hal.2012.11.001](https://doi.org/10.1016/j.hal.2012.11.001)) [published, refereed]
- Frolov, S. (2011a) “Do we have sufficient data to constrain coastal biogeochemical models: towards optimal design of ocean observatories?” Invited talk at the *Gordon Research Conference on Coastal Ocean Modeling*, South Hadley, MA.
- Frolov, S., J., Bellingham (2011b) “How convergent and divergent fronts structure the cross-shore gradients of physical, chemical, and ecosystem properties in Monterey Bay?”, *EPOC meeting*, Lake Tahoe, CA.
- Frolov, S., W. Anderson, G. Hine, J. Bellingham (2011c) “Wave Glider—a platform for persistent monitoring of algal blooms,” in *Proc. IEEE OCEANS*, Kona, HI. [published]
- Frolov, S., B. Garau, J. Bellingham Planning optimal synoptic surveys in presence of variable uncertainty and decorrelation scales: benefits of adaptive sampling. *Journal of Geophysical Research*. [submitted]

HONORS/AWARDS/PRIZES

Frolov, et. al. (2013) refereed article in *Harmful Algae* was the second most-downloaded article that was published in 2013.